61693

B061693

ok

CANADA

RESEARCH IN PREMIUM-QUALITY CASTINGS IN LIGHT ALLOYS

J. W. MEIER

DEPARTMENT OF MINES AND TECHNICAL SURVEYS, OTTAWA

PHYSICAL METALLURGY DIVISION

MINES BRANCH

RESEARCH REPORT

R 149

Price $1.00

JANUARY 1965

Available by mail from the Queen's Printer, Ottawa,
and at the following Canadian Government bookshops:

OTTAWA
Daly Building, Corner Mackenzie and Rideau

TORONTO
Mackenzie Building, 36 Adelaide St. East

MONTREAL
Aeterna-Vie Building, 1182 St. Catherine St. West

or through your bookseller

A deposit copy of this publication is also available
for reference in public libraries across Canada

Price $1.00 Catalogue No. M38-1/149

Price subject to change without notice

ROGER DUHAMEL, F.R.S.C.
Queen's Printer and Controller of Stationery
Ottawa, Canada
1965

Mines Branch Research Report R 149

RESEARCH ON PREMIUM-QUALITY CASTINGS IN LIGHT ALLOYS

by

J. W. Meier*

ABSTRACT

Extensive research on the structure and properties of cast aluminum and magnesium alloys has been applied to foundry practice. The term "premium quality" is used to describe castings with reliably high mechanical properties and high integrity of the product, guaranteed by the foundry. In production, conventional equipment and manufacturing techniques may be used, but rigid control of metal purity, alloy composition, melt quality, solidification conditions and heat treatment is essential to achieve and maintain high reliability of properties in designated areas of the casting, which are graded according to design and service considerations. Examples of the excellent properties that have been obtained in aluminum and magnesium alloy castings are listed.

Considering currently achieved properties, it is believed that in the near future aluminum alloy castings with 70 kpsi (50 kg/mm^2) UTS, 60 kpsi (42 kg/mm^2) 0.2% YS and 10% El., and magnesium alloy castings with 60 kpsi (42 kg/mm^2) UTS, 50 kpsi (35 kg/mm^2) 0.2% YS and 10% El., will be developed.

* Principal Metallurgist (Non-Ferrous Metals), Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, Canada.

A paper based on this report has been prepared for presentation at the 32nd International Foundry Congress, Warsaw, Poland, September 1965.

Direction des mines

Rapport de recherches R 149

RECHERCHE DE PIÈCES COULÉES DE HAUTE QUALITÉ EN ALLIAGES LÉGERS

par

J. W. Meier*

RÉSUMÉ

L'auteur a fait des travaux poussés sur la structure et les propriétés des alliages d'aluminium et de magnésium pour l'industrie. L'expression "haute qualité" s'applique aux pièces ayant des propriétés mécaniques élevées et à un produit supérieur, le tout garanti par la fonderie. En pratique, on peut utiliser un appareillage et des méthodes de production conventionnels, mais le contrôle rigoureux de la pureté du métal, de la composition de l'alliage, de la qualité du bain, des conditions de solidification et du traitement thermique, est essentiel si l'on veut obtenir et conserver l'excellence des propriétés de parties spécifiques de la pièce, parties qui sont classées en fonction du dessein et de l'usage de la pièce. L'auteur donne des exemples des propriétés excellentes obtenues dans des pièces en alliages d'aluminium et de magnésium.

En se basant sur les propriétés obtenues couramment, on croit pouvoir produire, dans un avenir rapproché, des pièces en alliages d'aluminium ayant une résistance à la traction de 70 kpsi (50 kg/mm^2), une limite conventionnelle d'élasticité (à 0.2%) de 60 kpsi (42 kg/mm^2) et un allongement de 10%, et des pièces en alliages de magnésium où ces valeurs seront de 60 kpsi (42 kg/mm^2), 50 kpsi (35 kg/mm^2) et 10%.

*Métallurgiste principal (métaux non ferreux), Division de la métallurgie physique, Direction des mines, ministère des Mines et des Relevés techniques, Ottawa, Canada.

Un exposé basé sur ce rapport a été préparé pour soumission au 32^e congrès international de fonderie, à Varsovie (Pologne) en septembre 1965.

CONTENTS

TABLES

FIGURES

INTRODUCTION

The general theme of the 32nd International Foundry Congress, to be held in Warsaw, Poland, from September 12 to 18, 1965, is "Scientific Investigations as a Source of Technical Progress in the Foundry". The theme of the previous Warsaw Congress, held in 1938, was "Cooperation between the Engineer and the Foundryman". The difference in the phraseology shows the evolution of the foundry industry in the past quarter century, from the ancient craft and long-established art of making castings, based on centuries of practical experience rather than on scientific principles, to the modern concept of premium-quality castings, made possible only by systematic research on casting fundamentals.

The most important reason for this change was the requirement of the designer and producer of modern engineering equipment for guaranteed quality of castings. In the past, the designer, if he could be persuaded to use cast products for mechanically stressed components, had to use a prohibitive "casting safety factor", which considerably limited the application of castings whenever strength-to-weight considerations were vital. The inability of the foundry industry to produce castings of consistent quality forced the designer to substitute forgings or parts fabricated from wrought products. This created, of course, considerable cost and time losses due to additional machining and joining operations, and, in many cases, also added weight.

The aircraft and, more recently, spacecraft industries were the first to insist on castings of guaranteed and strictly controlled properties. The reaction of the foundry industry was slow, because it was difficult to change their philosophy based on quantity production and dislike of the idea of guaranteed casting properties. There was, furthermore, an understandable hesitation to employ the skilled personnel necessary for the comparatively small volume of highest-quality castings.

A second reason for forcing the adoption of scientific techniques was commercial necessity in the battle for survival of the foundry industry. Modern trends toward the economies and efficiencies made possible by automation and mass production have resulted in a gradual and significant decline in the relative importance of the time-honoured sand-casting process over the past two decades. As shown in Table 1, in the aluminum alloy field the tonnage of die castings and permanent mould castings currently far outranks that of sand castings. Similarly, in the much smaller magnesium field (Table 2) die castings recently assumed first place in the U. S. casting production.

As an aid to the survival of sand foundries, much work has been done on the improvement of the surface quality and on closer casting tolerances, in order to minimize costly finishing and machining operations. It is evident that this approach has limitations imposed by the inherent characteristics of the sand-casting process. Consequently, the next obvious alternative was work on improving casting quality to take full advantage of the properties offered by the recently developed high-strength casting alloys.

Considerable research effort followed and it was demonstrated by various research institutions not only that high properties could be obtained in castings but also that these results could be obtained consistently.

Premium-quality castings can be made using any casting process, including sand moulds with chills, permanent moulds, shell moulds, investment moulds, etc. Most of the pioneer work on premium quality was carried out on heavily chilled sand castings, although some permanent mould and investment castings were also produced.

PREMIUM QUALITY CONCEPT

What is "premium quality"? It is not only better internal quality of the casting and resultant higher mechanical properties, but the most important feature is the high integrity of the product, that is, the reliability of properties in designated areas of each and every single casting, which are guaranteed with confidence by the foundry. To achieve this, it is necessary to have higher purity of metal and closer alloy composition limits; strict quality control in each individual melting, casting and heat treating operation; proper mould design to obtain optimum solidification conditions in designated areas of the casting; and careful evaluation of casting properties.

The novel concept of "premium-quality castings" guaranteed by the foundry is representative of the quiet "revolution" which is modernizing the casting industry to make possible the production of scientifically engineered castings. To survive, the foundry industry has to substitute research and education for tradition and trial-and-error experience.

It should be noted that, in the production of premium-quality castings, conventional equipment and manufacturing techniques are used; the only departure from traditional founding is that each foundry operation has to be carefully studied and, once established, strictly controlled.

The most important problem is the appreciation and understanding of all the many factors affecting the soundness of the casting and its mechanical properties. An earlier paper(1) lists some 50 such factors related to the alloy composition, melting conditions, casting procedure, casting design, heat treatment, test bar preparation, and test variables.

Work leading to the development of premium-quality castings has been undertaken by various research organizations, of which, in particular, the systematic efforts at the Massachusetts Institute of Technology(2, 3, 4) are notable. Industrial work has followed, usually in close cooperation with the aircraft industry. Considerable improvement in mechanical properties obtainable in critical areas of castings was achieved and reported by Nelson(5), Gronvold(6), Bailey and Bossing(7), Iler(8), Lagowski and Meier(9), and others.

The cooperative effort was so successful that, recently, U. S. Military Specifications for High-Strength Aluminum(10) and Magnesium

Alloys[11] were issued, which for the first time specify minimum properties in designated areas of castings, graded according to the importance of the area from design considerations. Table 3 presents minimum properties specified for test bars cut from designated areas of premium-quality castings for two high-purity aluminum-silicon base alloys. Because the magnesium alloy specification was discussed recently by Nelson[12] and Mann[13], in order to avoid undue repetition Table 4 shows only the specified values for the three alloys of highest strength. It should be emphasized here that the specified properties are minimum requirements for the designated areas of each casting, guaranteed by the producer, and not maximum or optimum values obtainable as noted by Mann[13].

Premium-quality castings are, of course, more costly than ordinary commercial castings and should be used mainly in highly-stressed parts for service under severe conditions or substituted for parts fabricated from wrought alloys, where the highest strength-to-weight ratio is essential. However, taking into consideration the fact that castings can be made to almost any final shape and to reasonably close tolerances, it seems that the higher material cost of premium-quality castings can often be offset by elimination of machining and other fabricating costs associated with wrought products.

The following sections of this paper contain a brief review of research problems that are directly or indirectly vital to the concept of premium-quality casting. It is not intended to describe in detail the various foundry control operations[32, 33, 34], but only to indicate such aspects of melt quality, casting procedures and heat treatment associated with the production of premium-quality castings, as have been reported in the past few years by various research workers. The paper is concluded by a short account of some modern methods for the evaluation of guaranteed-quality castings and some remarks on the likely direction of future trends in the continuing research and development work.

ALLOY RESEARCH

Aluminum Alloys

In the commercial aluminum casting alloys, no radically new alloy compositions have been introduced in the last decade or so. Most of the research and development work has been associated with improvements in casting alloys by use of high-purity metals, by modifying slightly the composition limits and/or by varying heat treating cycles. Table 5 lists some of these improved sand casting alloys, selected from the point of view of their usefulness in premium-quality castings.

Most of the work on premium-quality casting alloys has been devoted to aluminum-silicon alloys, which are known for their excellent foundry characteristics. The two high-strength alloys in this series are SG70-T6 (or commercial alloy 356) and SC51-T6 (or alloy 355). By comparing typical test bar values obtained on commercial alloys[14] the effect of using high-purity metals(3) on the mechanical properties of alloy SG70A is shown in Table 5. The influence of heavy chilling to obtain improved solidification conditions is shown in the same table by comparing results obtained on unchilled and chilled castings(15). Furthermore, the effects of changes in the alloy composition are also illustrated by the properties reported(16) for sand-cast alloys 356 variant-T6 (higher Mg, added Be) and 354-T6 (higher silicon and magnesium, added copper). Similar results have been observed(17) for the effect of high purity on the properties of alloy SC51A-T6.

Considerable work on the improvement of properties, especially ductility, of aluminum-4.5% copper alloy C4-T6 was carried out with very successful results, at the Massachusetts Institute of Technology(2, 3, 18), as indicated by the values presented in Table 5.

In the aluminum-magnesium system, the aluminum-10% magnesium alloy G10-T4 has excellent mechanical properties, especially high ductility, and has good machinability and high corrosion resistance. However, this alloy has less favourable foundry characteristics than other high-strength alloys and is susceptible to stress-corrosion cracking. High purity is essential for optimum properties(18, 19), as shown in Table 5. Better resistance to stress corrosion and greater stability during natural ageing may be obtained by the addition of zinc(20).

Magnesium Alloys

Research on magnesium casting alloys may be divided into three categories: (a) improvement of the long-established Mg-Al-Zn alloys, (b) development of new high-strength alloys for service at room temperature, and (c) development of alloys for service at elevated temperatures. The nominal composition and typical properties of most of the commercial and some experimental magnesium sand-casting alloys are listed in Table 6.

(a) Mg-Al-Zn alloys are the oldest and still the most generally used of magnesium casting alloys. Investigations into improvements of these alloys are mainly directed towards increasing the mechanical properties of production castings. Improvements are achieved by proper solidification control[4,5], changes in heat treating cycles[14], water quenching after solution heat treatment[5,13,21], small alloying additions[13], and developments in refining techniques[22].

(b) Research on high-strength magnesium alloys has been based principally on the important discovery by Sauerwald[23] that zirconium additions to magnesium and some magnesium alloys produce marked grain refinement. British alloy Z5Z (or ZK51-T5)[24] was the first commercial alloy containing zirconium and showed a significant increase of yield strength and elongation values over those for the standard Mg-Al-Zn alloys. The introduction of the Canadian alloy ZK61-T6[25,26], which is amenable to high-temperature heat treatment, created the first high-strength, high-ductility magnesium casting alloy; this alloy has the highest strength-to-weight ratio of any commercial non-ferrous casting alloy. Unfortunately, both of these alloys, ZK51 and ZK61, have rather unfavourable foundry characteristics and high-quality castings can be obtained only with very careful melting (to obtain high effective zirconium content) and casting (mould design and solidification conditions) procedures. British work[24] on additions to Mg-Zn-Zr alloys of rare earth metals (alloy RZ5, or ZE41-T5) or thorium (alloy TZ6, or ZH62-T5) was very successful in improving casting and welding characteristics, but resulted in suppressing the response of these alloys to high-temperature heat treatment and, therefore, in lower tensile properties.

A more recent development of high-strength magnesium casting alloys is the Canadian work[27,28] on the Mg-Zn-Ag-Zr alloy system. Figure 1 shows average tensile property values for fully heat treated alloys of this group, obtained on separately-cast test bars. Table 6 also lists some of the compositions which show considerable promise of being especially suited for premium-quality castings. Some of the alloys (ZQ64, ZQ71, ZQ91) show a combination of strength and ductility much superior to that obtainable on any of the present commercial casting alloys; other alloys (ZQ32, ZQ42, ZQ52) show very high elongation while retaining considerable tensile strength and could be used for some structural applications where high ductility is desirable.

Additional work with ZQ-type alloys on end-chilled plates of 1- and 2-inch thickness(9), on thin-walled premium-quality castings(28) and on a massive prototype casting(29) showed properties equal to, or better than, those obtained on separately-cast test bars. Alloy ZQ64-T6 had, in some designated areas of castings, UTS up to 51,200 psi (36 kg/mm^2), 0.2% YS up to 43,200 psi (30.5 kg/mm^2), and elongations in the range from 5 to 16%. Alloy ZQ91-T6 showed(28) exceptional potentialities for application in thin-walled premium-quality castings, because of its excellent foundry characteristics, especially good fluidity and freedom from unsoundness.

(c) Work on alloys for short-time service at elevated temperatures has included alloys containing rare earth metals (alloy ZRE1, or EZ33-T5), which are used up to 290 °C (550 °F), and alloys containing thorium (alloys HK31-T6, and ZT1, or HZ32-T5), which are used up to 340 °C (650 °F). The most recent addition to this group is the British alloy MSR (or QE22-T6)(30, 31), which is the strongest alloy at elevated temperatures up to 260 °C (500 °F), and possesses good foundry and welding characteristics. Although this alloy also exhibits a high yield strength at room temperature, which is little affected by the distance from chill(9), the ultimate tensile strength and the elongation are relatively low. Thus, the suitability of this alloy for premium-quality castings is limited, because an ample margin of UTS over YS and good ductility increase the reliability of castings from the designer's point of view.

MELT QUALITY

One of the most important aspects in the production of premium-quality castings is the control of the metal preparation to ensure that highest melt quality is attained. The main factors affecting melt quality are: careful choice of the metal charge, to obtain low impurity contents and optimum alloy composition; cleaning of the melt from non-metallic inclusions, and thorough degassing; effective grain refining; protective covering of the melt (if necessary for the particular alloy); strict temperature control during all melting and refining operation; and avoidance of long holding times.

The effect of high purity on mechanical properties of aluminum alloys was shown previously in some examples given in Table 5. Although the deleterious effects of iron on Al-Cu (C4) and Al-Si (SC51, SG70) alloys, and of silicon and sodium on Al-Mg (G10) alloys, have been known for some time, high-purity metal has not been used in commercial alloys because of economic considerations. However, for the best mechanical properties high-purity metals must be used.

Very narrow composition ranges for alloying elements (much closer than those allowed in commercial specifications) are necessary in some alloys for maximum strength or ductility, e.g., the magnesium content in aluminum alloys SG70 or SC51, or the didymium content in magnesium alloy QE22. Special care has to be taken to achieve the highest possible soluble (or effective) zirconium content in high-strength magnesium alloys[26, 33]. Since strict adherence to alloy composition is of great importance, equipment and techniques for fast analyses (such as a direct-reading spectrographic apparatus) are very desirable for checking the melt before pouring.

The melt quality is very much affected by oxides and other non-metallic inclusions[34, 35], and great care should be taken to clean the melt. For this purpose a great variety of proprietary fluxes has been developed and the various methods of melt cleaning have been described for aluminum[14, 36] and for magnesium[33] alloys. Recently, considerable interest was shown in achieving a more efficient elimination of inclusions by various filtering methods[36, 37, 38]. A rapid test for inclusion content is being studied[39] which uses gas in a molten sample to float inclusions to the top surface during slow solidification under vacuum.

Thorough degassing of the melt is essential for high-quality castings and this can be achieved in various ways, such as by bubbling insoluble and reactive gases through the melt, the decomposition of solid degassing agents, vacuum degassing, and vibration[14, 32, 34, 40]. Degassing of magnesium alloys containing aluminum is carried out by treatment with chlorine or volatile chlorides[33]. In zirconium-containing magnesium alloys, special degassing operations are not used, because hydrogen is incompatible with zirconium[24].

To assure the efficacy of the degassing treatment, an effective quality control method is necessary. There are numerous test methods[34, 40] available, ranging from the semi-quantitative reduced-pressure test and various density-measuring methods to the quantitative Telegas instrument and the newest nuclear method of using radioactive isotopes[41].

Grain size is important, too. There are basically two factors affecting the grain size of light alloy castings; these are the solidification rate and the presence of grain-refining elements. Ruddle and Cibula[34] state that in cast alloys of cubic structure the influence of grain size "per se" is negligible; nevertheless, the mechanical properties are very much affected by grain size, because of its influence on the shape and magnitude of the shrinkage voids and on the accompanying morphology and size of microconstituents at the grain boundary[42]. Inevitably, both are present to some extent in castings of long-freezing-range alloys. In magnesium-base alloys, grain size and mechanical properties have been found to be directly related[1, 26].

In aluminum alloys effective grain refining is obtained by additions of various commercial hardeners and proprietary grain-refining fluxes, mostly based on titanium and boron[14, 34, 43]. Coarsening of grain size may occur if too high melting or pouring temperatures, or too long holding times, are used[18, 43]. Grain refining by sonic and ultra-sonic vibration of aluminum castings has shown promising results and has yielded increased tensile properties[45]. Magnesium alloys containing aluminum are grain refined by superheating or by additions of carbon-containing compounds[33,44]. Most other magnesium alloys are grain refined by the addition of zirconium[23,24,25,26].

A fast check on grain refinement of the melt may be made by pouring a small fracture bar sample, quenching it in water as soon as it is frozen, notching and breaking it for examination of the fracture, and, if necessary, comparing with an established standard. This type of test is used successfully in zirconium-containing magnesium alloys[26,33]. A check of grain structure throughout the casting can be made only by metallographic examination, although here again fracture testing of various sections is useful.

Protective cover fluxes prevent the formation of oxides during melting or prolonged holding of the melt. In most aluminum alloys the self-generated aluminum oxide cover film is sufficient to protect the melt, but in all magnesium-base alloys[33] special cover fluxes must be used.

The importance of strict temperature control in melting operations cannot be overemphasized and is an essential factor in the production of high-quality castings. Pouring temperature requirements may dictate an abnormal range, because of size and configuration of the casting, but, in general, melting and refining temperatures for most aluminum alloys should be held as low as possible. In order to avoid grain coarsening, deterioration of mechanical properties[18] due to excessive gas pick-up or increased oxidation and loss of magnesium, temperatures should not exceed 720-730 °C (1330-1350 °F). Magnesium-base alloys containing aluminum have an optimum melt temperature range of 720-760°C (1330-1400°F), unless superheating at 900-925°C (1650-1700°F) is applied for grain refinement. For magnesium alloys containing zirconium, melt temperatures should be kept in the range of 740-800°C (1370-1470°F). Accurate temperature controlling and recording instruments are essential to high-quality foundry practice, and they should be regularly checked.

Long holding times at higher melt temperatures should be avoided, because castings produced from such melts may show decreased mechanical properties[1, 18] due to grain coarsening and gas pick-up.

Control of melt quality is normally applied through tests on separately-cast test bars[1,46]. These test bars are not intended to represent the properties of production castings of various shapes and sizes, but are used throughout the foundry industry to check melt quality and heat treatment, as well as for research or development work on alloy compositions or heat treating techniques. In North American practice these test bars are cast-to-shape in green sand (without use of chills) and tested without machining. As in all test methods, in order to obtain reproducible results, production of these test bars must be strictly standardized by control of such factors as mould design, sand and moulding conditions, pouring temperature, pouring speed, etc.

LIQUID METAL FLOW

All the precautions to achieve a high melt quality will be wasted if the method of delivery of the molten metal into the mould cavity adversely affects the metal quality. Care must therefore be taken, during the pouring and mould filling operations, to prevent flow disturbance, gas entrainment, mould erosion, etc.

Pouring temperatures[1, 18] and techniques[33, 34, 35] are of considerable importance to the quality of the castings. For aluminum alloys the lowest possible temperature should be used for magnesium alloys, optimum pouring temperatures are in the range of 730-800 °C (1350-1470 °F), depending on the alloy composition. Minimizing the pouring height, using a properly designed pouring basin and keeping it full of metal, as well as carefully skimming the melt surface to avoid flux or dross inclusions in the metal stream, are obvious precautions known to every foundryman.

A constant pouring rate is of utmost importance for the quality of the casting, and the pouring stream of the metal must be maintained unbroken until the mould is filled. Considerable research on the principles of sprue design and gating has been carried out in the past 15 years. Especially noteworthy is the extensive work carried out in this field by the Battelle Memorial Institute under the sponsorship and guidance of the

Light Metals Division, American Foundrymen's Society[47]. Excellent accounts on this subject are available[34, 48, 49]. Special precautions are necessary in the handling of magnesium-base alloys[33]. Results of a study on gating for premium-quality castings were reported recently[50].

It should be appreciated that, in order to ensure the highest quality product, the gating design for each individual casting is a separate problem in itself. A modern approach to the study of metal flow in the mould was embodied recently in the use of fluorescent screen radiography[51].

Any discussion of liquid metal flow would be incomplete without noting the importance of some physical properties of liquid metals and alloys. From the foundrymen's point of view the most important is the "casting fluidity", which covers two phenomena. The first is the ability of the metal to flow through narrow sections (e.g. fluidity spirals), and the second is the ability to fill a complicated mould cavity and to penetrate into sharp corners. An extensive review of the basic theory of fluidity and of some practical application of the theory to the production of thin-section castings was recently published by Flemings[52]. Alloy composition, heat content, heat transfer, metal velocity, and mode of solidification are the major factors affecting fluidity, while surface tension becomes important in ultra-thin sections. It seems that more work to develop a better understanding of liquid metal properties would be very beneficial for future improvement of the casting process.

SOLIDIFICATION

Our knowledge about the various aspects of solidification and heat extraction in the mould is growing and a considerable number of publications on these subjects are available[2, 34, 53-71]. From the point of view of the foundryman, the most important feature is the effect of the mode of solidification on the soundness and the mechanical properties of the casting.

For most practical purposes the ideal casting is one which is sound, has a fine structure (grain size, dendritic cell size, and alloy constituents), and is free from macroscopic segregation. However, the factors that the foundryman has to consider in attempting to accomplish this ideal, such as gating, risering, chilling, section thickness, complexity of shape, etc., cannot be taken independently because they affect more basic variables, such as cooling rate, direction of the heat flow, and thermal gradients at various points in the casting. In broad terms, the cooling rate determines the fineness of the structure and the other variables affect the soundness.

For example, the use of chills usually results in increased cooling rates in most of the casting. However, although an increased cooling rate in itself may benefit mechanical properties by giving a finer structure, this is often secondary to the improved soundness obtained by proper directionality of solidification and higher thermal gradients. Similarly, although it is common foundry experience that thick sections in castings usually have lower properties than thin sections (owing mainly to the difference in cooling rates), in correctly chilled castings it is easier to induce proper directional solidification, and therefore, under certain conditions, greater soundness in heavier sections is obtained with correspondingly higher properties (see Table 7).

It is difficult to apply the results obtained in laboratory tests, designed to determine the effects of only one or two factors in comparative isolation, to most industrial castings, because here the various factors mentioned above are combined in a highly complex manner. However, it is important that work on both aspects -- that is, basic research and the application to practical problems -- should be continued. Studies showing the inter-relation of various factors affecting the mechanical properties of castings, such as that recently reported for gas content and solidification rate of three aluminum alloys[58], would be especially useful.

No discussion of solidification would be complete without some reference to defects that can be introduced at this critical stage of the casting process. These include microporosity, hot tearing, and segregation.

Microporosity is a defect which is usually caused by a combination of solidification shrinkage and precipitation of gas (hydrogen in light alloys). In a very well-fed casting made with gassy metal the defect will be predominantly gas porosity, and in a poorly-fed casting made with thoroughly degassed metal the porosity will be predominantly "microshrinkage". The various types of microporosity have been discussed earlier[33,34], and special reference may be made to the particularly deleterious layer-type porosity which occurs readily in Al-10% Mg alloys[19] and in some magnesium alloys; it is also related to hot tearing.

Hot tearing is caused by contraction restraint during the solidification of the metal in a mould,and occurs at a temperature slightly above the solidus of the alloy. The main factors in hot tearing are: casting and mould design (contraction restraints, hot spots, etc.), thermal gradients, alloy composition,and grain size. Classifications of light alloys according to their hot tearing tendency[14] are based on various laboratory tests[59,60] and on industrial experience. It was reported recently by Russian investigators that vibration during solidification markedly reduced the hot tearing susceptibility of some alloys because vibration induced healing of the tears.

Macrosegregation involves the mass movement of solute-rich liquid and this may occur by a number of related mechanisms. In light alloys, the most common segregation phenomenon is "inverse segregation", in which the solute enrichment occurs towards the freezing face, leading to considerable variations from the nominal composition[9,19]. This may have serious effects on the properties of the casting.

Considerable segregation can sometimes result when voids or cracks in a casting are produced by highly localized shrinkage. These "incipient" hot tears may then be filled with lower-melting-point, solute-rich liquid. Examples of this form of segregation have been noted in some magnesium alloys[59]. Skelly and Sunnucks[61] investigated magnesium-rare earths alloy castings in which the segregations were observed as marked X-ray indications, but test bars cut out of these areas showed no deterioration of mechanical properties. It is believed that this type of "defect" is quite widespread in other alloys, where it may not be as easily detected. The effect of this kind of segregation on the properties of castings is still the subject of considerable controversy and is probably dependent on the location and degree of segregation in any particular casting.

Microsegregation -- that is, variation in solute elements over distances of the order of half the dendrite arm spacing -- has an important bearing on the properties of castings and on the time and temperature requirements for subsequent homogenization. Flemings[62] has shown that the degree of segregation can be accurately predicted theoretically from constitutional diagram data. At the same time, it was shown that, although increasing the cooling rate does not have a significant effect on the degree of microsegregation, the distance between the points of highest and lowest solute content is reduced and this may have an important effect in facilitating subsequent homogenization. Mechanical properties of castings having severe microsegregation may be substantially improved by intensive homogenization treatments.

CASTING PROCESS

As has been previously stated, premium-quality castings can be made in any casting process, including not only chilled sand castings, permanent mould castings, shell mould and investment castings, but also castings produced by centrifuging or solidification under pressure. Iler(63) and Smith(64) demonstrated that sounder and stronger castings of thin-walled sections with very close dimensional tolerances can be obtained by using centrifugal casting. Low-pressure casting of aluminum alloys, similar to casting into partly evacuated moulds, was used during World War II for some aircraft castings in order to obtain great dimensional accuracy, fine detail in very thin sections, and better casting soundness. More recently, an investigation(65) on the effect of pressure during solidification showed marked reduction of microporosity. The use of ultra-high pressure (up to 100,000 psi or 7000 at.) during the solidification of aluminum alloy A356 (Al-7Si-0.3Mg) consistently produced excellent soundness, high strength, and unusually high elongation(66).

Pressure die casting is recognized for its ability to mass-produce castings of very close tolerances and good surface finish, but die castings are not distinguished for their internal soundness or reliably high mechanical properties. Considerable research is being directed both to the study of factors affecting the quality of pressure die castings, including the flow of the injected metal, heat transfer in the die, the use of vacuum, and amenability of die castings to heat treatment, and to the design of machines capable of higher pressures. It would be much too early to predict that premium-quality castings can be consistently produced by this process, but, taking into consideration the rapid progress in automation and the possibility of computer coordination of metal flow, die evacuation, heat extraction, pressure, and proper solidification conditions, it seems a reasonable prospect for the not too distant future.

In sand casting, great progress has been made in mould materials. Numerous investigations of moulding sand variables, and new moulding techniques such as the shell moulds (Croning process), CO_2-hardened cores, thermosetting and air curing binders, etc., have considerably improved the surface quality and dimensional accuracy of the castings. Precision sand-casting methods (e.g. the Osbrink process) have made it possible to cast sections as thin as 0.08-in. (2 mm)[67] or less. The degree to which close tolerance castings and good surface finish can be achieved rests, of course, inherently in the casting process chosen and in the skill and care with which it is carried out. Pattern equipment of great accuracy (in some cases, prepared by tool makers), rigid and close fitting flasks, and great care in mould handling are the most essential factors in precision production of castings. The external precision quality of castings has nothing to do with the concept of premium-quality casting, as defined earlier, but is important from many other points of view, including the competition of high-strength castings with wrought products or fabricated assemblies.

A very interesting recent innovation is the "Full Mould Process", where foamed polystyrene is used to produce patterns which are left in the mould and decomposed by the molten metal as the mould is filled. The main advantages are that there are few, if any, restrictions on the shape of the patterns and smoother finishes may be possible in some instances. A further development of the process is the use of unbonded sand, which would have promising possibilities in the fully automated production of sand castings.

HEAT TREATMENT

Standard heat treating procedures have long been established[14] throughout the industry, and should be followed with great care and a somewhat higher degree of precision in the production of premium-quality castings. High accuracy in furnace temperature control, and uniformity of temperature throughout the load, are of special importance. The particular solution heat treating temperature must be very carefully established for each alloy composition (if possible, with the aid of solidus determinations), and the highest "safe" temperature should be used within very close limits ($\pm$ 2 °C). It is essential, therefore, that the temperature control throughout the whole furnace be kept within these limits and that, to avoid difficulties, a controlling thermocouple be placed within the furnace load to continuously record the temperature. The time of solution heat treatment will depend on the alloy composition and the average section thickness of the castings treated in a furnace batch. For magnesium alloy castings, automatic control of protective atmospheres (usually SO_2) in solution heat treatment should be mandatory.

In some alloys, the time interval between the removal from the solution heat treating furnace and immersion in the quenching bath is very critical, and to achieve high properties this time interval must be kept to a minimum (in seconds, not minutes !). Another important factor is the cooling rate from the solution temperature. For most aluminum alloys, quenching in water at 65 - 100 °C (150 - 212 °F) is generally used. For most magnesium casting alloys, cooling in still air or a forced air-blast is sufficient, although for highest properties quenching in hot water is being used[5,21,28]. More drastic quenching rates (oil, cold water) should be avoided because of the danger of warping or cracking the casting, and of introducing high internal stresses.

The time interval between solution heat treatment and artificial ageing is also important in some alloys, and its effect should be established for optimum and consistent properties. The establishment of proper ageing temperatures and times should be very carefully investigated because of their effect on the most important design criteria: yield strength and elongation.

PROPERTIES OF PREMIUM-QUALITY CASTINGS

To illustrate the remarks on solidification conditions and heat treatment, some examples[9] of the effect of heavy chilling and some modifications of the heat treating cycles are shown on end-chilled plates (Figures 2 to 6, and Table 7), followed by a tabulation[29] of properties obtained in production castings (Table 8).

Figure 2 shows the effect of end-chilling on the mechanical properties of a 2-inch (50.8 mm) plate cast in magnesium alloy ZK61-T6 (Mg-6 Zn-0.8 Zr). The test bars were cut, at 1/4-inch (6 mm) intervals, parallel to the chilled face. Additionally, the graph also shows the effect of a modification in heat treatment. Exceptionally high properties were obtained at the chilled face, but even the test bars cut out at a 4-inch (10 cm) distance from the chill (which solidified predominantly under the influence of the adjacent riser) show very good properties.

Figure 3 illustrates the effect of plate thickness on properties of alloy ZK61-T6 and further shows the importance of chilling for heavier sections (1- and 2-inch, 25.4 and 50.8 mm).

Figures 4 and 5 show the effect of end-chilling on various Mg-Al-Zn and high-strength magnesium alloys containing zirconium. The properties decrease with increasing distance from the chilled end and consequent coarser grain size. The grain size of Mg-Al-Zn alloys increases considerably with increasing distance from the chilled face, whereas alloys containing zirconium show only a relatively small difference in grain size. Accordingly, the graphs show that the Mg-Al-Zn alloys are much more sensitive to the distance from the chill. These results indicate that, in order to obtain optimum properties in these alloys, chilling and risering have to be closely spaced to produce steep thermal gradients. The high properties of alloy ZK61-T6, and especially those of the experimental alloys ZQ64-T6, ZQ71-T6 and ZQ91-T6, are noteworthy. Such combinations of mechanical properties are not obtainable in any other magnesium alloys, and compare favourably with specified properties of wrought magnesium alloys.

Figure 6 illustrates the considerable effect of changes in solution time, cooling rate from the solution temperature, and ageing time on the mechanical properties of an end-chilled 2-inch (50.8 mm)-thick plate sand cast in magnesium alloy ZK61-T6 (Mg-6 Zn-0.8 Zr).

Table 7 lists properties of various sand-cast magnesium alloys obtained on separately-cast test bars, and on premium-quality castings of three different section thicknesses. The results show that properties can be obtained in cast sections which are equal to, or better than, those obtained on separately-cast test bars, irrespective of section thickness.

To check the results obtained on test plates, a series of over 50 magnesium alloy production castings (each about 12 kg net weight) was sand cast by a commercial foundry, using premium-quality procedures.

Table 8 shows the results obtained in Class 1 designated areas and in unspecified areas of the castings, and it will be seen that these were generally much better than the stringent requirements of the specification for premium-quality castings (see also Table 4). Results are also listed for simulated service tests (break-down tests of entire castings under static load), showing that the ZK61-T6 alloy castings had 30% higher strength than the standard aluminum alloy forging used for the same purpose and which weighed about 10% more.

EVALUATION OF PREMIUM-QUALITY CASTINGS

The problem of evaluation of product quality must necessarily be considered when the order for a new casting shape is discussed, since it is implicit in the concept of premium quality that the production of the casting has to be planned from the design stage to the final acceptance by the user. It will be apparent from this paper that a thorough discussion of the design between the foundryman (or rather casting engineer) and the designer will prove useful to both. The designer will wish to impart to the foundry engineer an understanding of the functional use of the casting and a knowledge of the critical areas destined to withstand severe conditions. On the other hand, the foundry expert may be able to point out detail design modifications which may assist in production or ensure high quality without compromising the essential purpose of the casting. At the same time, all quality requirements and the exact quality control and inspection procedures have to be established and mutually agreed upon.

The next step is the foundry engineering stage, where the proper casting conditions (selection of casting process, mould geometry or die design, chilling and solidification conditions, etc.) and heat treating cycles have to be decided upon. Foundry experience, records of procedures used in the past for the casting of comparable shapes, and the practical application of results of recent research work, are all essential to the planning stage. Comprehensive written instructions for each individual job should be issued and the documentation established (metallurgical practice form, including gating, risering and chilling information, and specification and inspection requirement form) which follow each individual melt or heat treating batch through the foundry. Formal record keeping of these documents is essential for planning of future work.

Once the foundry is satisfied with its procedure, prototype castings should be submitted to the customer for inspection and acceptance. The inspection of prototype castings should be thorough. Whenever possible, non-destructive testing should be used to check the soundness of the casting but, otherwise, inspection should include: mechanical testing of test bars cut from critical sections, and of separately-cast test bars supplied by the foundry for each batch; metallographic examination of specimens taken from the critical sections of the casting, to establish the soundness, constituent size and distribution, and any correlation of structure and grain size with mechanical test results; and fracture tests in critical sections of the casting (very often a most useful check of casting quality).

While the foregoing testing techniques are invaluable, the ultimate confirmation of the utility of a casting can only be obtained by actual performance in service or, at least, by a test under simulated service conditions (e.g.,break-down test of a whole casting or of a critical casting section).

If the results of the inspection tests are acceptable to the user, the melting and casting procedures, as well as the heat treating cycles, should be standardized. Subsequent changes should not be made without agreement with the user, and should be based on additional tests.

Once in production, castings of the same design should be accepted on the basis of melt quality tests (on separately-cast test bars), casting quality tests (radiographic or other non-destructive tests), and a check of fracture, metallography and mechanical tests on specimens cut from critical sections of a small number of production castings chosen at random from different supply batches.

Great care is essential in choosing specimens[68] for mechanical testing. It is important that the full casting section be properly represented (flat bars have often to be used), that the largest possible size of the test bar be employed, and that in heavy sections the test bar be selected from a representative location.

However, insofar as non-destructive testing is concerned it is important to realize that a clear (no visible defects) radiograph does not guarantee premium-quality properties. As was previously observed, the highest mechanical properties can be obtained only when the proper solidification (grain size, dendritic cell size, micro-constituents) and heat treating (microsegregation) conditions prevail. Very fine porosity can escape detection by radiography, in which event the fracture test is a very useful supplementary check on quality.

Nevertheless, non-destructive testing has, in the last decade or so, shown great progress and numerous new developments have brought us closer to the time when most of our products will be tested without destruction of costly premium-quality castings. Fluoroscopic methods of high brightness or of high definition, using image amplification, may allow satisfactory replacement of more costly radiography. On the other hand, there are many new developments in radiography, such as high voltage units, new low-energy isotopes, better film quality, stereoradiography, and neutron radiography.

Other non-destructive tests developed or improved recently are: sonic and ultrasonic testing (grain size, section thickness, density); the use of eddy currents (chemical composition, density, hardness), of liquid penetrants (surface discontinuities), of microwaves (internal flaw detection), of electrical conductivity (temper of alloys, hardness), and of stresscoat (stress analysis, very useful in testing of prototype castings); and pressure testing (pressure tightness of castings).

More and more,non-destructive testing is being introduced in the examination of high-quality castings, and it is hoped that further progress in this direction will allow the user of castings to evaluate the product without the excessive cost and the unnecessary loss of time involved in machining great numbers of test bars, even in prototype development work.

Another important problem for the foundry is the determination of the origin of defects so that remedial action can be taken. Examples were recently reported on the use of modern scientific tools, including the electron-probe microanalyser for the detection of hard spots[41], and the examination of inclusions by radiographic, metallographic, X-ray diffraction and micro-spectrographic methods[69].

Statistical methods in quality control and data processing are very helpful in keeping the consistency of production variables within the limits necessary for premium-quality casting.

FUTURE TRENDS

"Why Bother with Premium-Quality Castings ?" was the title of a recent talk[70] and the answer was that "sooner or later a foundry must get into the premium-quality business or recede into a secondary casting operation with second-rate profits". While the premium-quality concept is currently applied to the aircraft and spacecraft industries, it has significance to the whole foundry industry - to the ultimate benefit of all.

In this day and age of fierce competition from alternative materials, castings can no longer be considered as simple shapes, and all castings, even those made from the cheapest materials, will eventually have to be designed to optimize weight, aesthetic appeal, and cost, if the foundry industry is to survive.

Mechanical properties to be expected in the near future, if present trends in alloy research continue, are summarized in Table 9. The properties of the strongest commercial aluminum and magnesium alloys now available, results achieved in recent experimental work, and expectations for the near future are compared with the mechanical properties of premium-quality steel castings. It is apparent that the strength-to-weight ratios of the light alloys compare very favourably with those of cast steel.

Further increases in strength could be achieved by an additional amount of cold work (by press-forging or similar hydraulic pressure processes) on premium-quality cast shapes[9]. High-pressure die casting at low temperatures (in the "mushy" state), more work on ultra-thin sections, die-casting dies cast to shape or prepared by use of powder metallurgy, and other similar developments may prove in the future to be useful in further extension of the casting industry.

Automation and mass production received a powerful impetus from computing devices. The potential uses of computers for metallurgical purposes, as recently described by Zotos[71, 72], appear to be very promising and have excellent possibilities in this field for the modern foundry. Indeed, computer-controlled melting, casting, heat treating and testing operations are to some extent already used. Evaluation methods for castings, using computers, depend on further progress in precision and speed of quality control equipment. In premium-quality-casting foundries, where work instructions must be issued and quality control results recorded and quickly related to other (memorized) data, the use of computers is invaluable and will open new horizons for the production of the highest-quality, lowest-cost castings with guaranteed properties. Through the standardization of functions, programming of normal applications is becoming simpler, and reliability of an extremely high order is available[73].

* * *

If one may be permitted to venture an opinion on the prospects for entirely new cast products from the foundry industry of the more distant future, it is evident that these lie in the general area of novel materials systems. This covers the field of unconventional combinations of cast metal and one or more added structural phases which may be metallic, intermetallic compound, ceramic, or gas. Such products include dispersion-strengthened alloys made, not by the usual solution and precipitation route, but by such techniques as interaction between dissimilar melts at the instant of pouring, mechanical dispersion by impressed energy (ultrasonic?), or electrodynamic melting. Is it asking too much to speculate that metallurgical processes, analogous to those now applying to colloidal chemistry or the development of metallurgical surface active agents, may not render possible the economic production of useful cast materials at present completely unimagined?

Going from the microscale to the macroscale, the application of high-strength metallic or non-metallic fiber reinforcements in castings offers intriguing prospects in the creation of unique materials, just as the deliberate and controlled addition of gas porosity has led to the creation of foamed metals, combining durability with lightness and ease of working and handling.

The future is before us and holds the promise of many interesting and useful developments in the adaptation of cast metals to the service of mankind. It should never be forgotten that such progress will be founded on the heritage of experience and knowledge of past generations dedicated to development of the metal industry of which the foundry is the cradle.

REFERENCES

1. J. W. Meier - "The Effect of Various Factors on the Mechanical Properties of Magnesium Alloy Castings" - Proc. 25th Internat. Foundry Congress, Brussels, pp. 223-240 (1958).

2. M. C. Flemings and H. F. Taylor - "Adapting Theory to Practice in the Manufacture of Light Metal Castings" - Proc. 25th Internat. Foundry Congress, Brussels, pp. 149-171 (1958).

3. M. C. Flemings - "Premium-Quality Aluminum Castings" - Foundry 91(7), 60-63, and (8), 47-49 (1963).

4. M. C. Flemings and E. J. Poirier - "Premium-Quality Magnesium Castings" - Foundry 91(10), 71-75 (1963).

5. K. E. Nelson - "Premium-Quality Magnesium Sand Castings" - Trans. AFS 69, 756-766 (1961).

6. W. Gronvold - "Short-time Elevated Temperature Properties of Premium-Quality Magnesium Castings" - Trans. AFS 68, 97-106 (1960).

7. W. A. Bailey and E. N. Bossing - "High-Strength Aluminum Alloy Airframe Castings" - Trans. AFS 69, 494-496 (1961).

8. A. J. Iler - "Castings - Aerospace Applications" - Annual Meeting, Castings Section, American Ordnance Assoc., Washington, 1964, pp. 36-39.

9. B. Lagowski and J. W. Meier - "Premium Strength in Sand-Cast Magnesium Alloys" - Trans. AFS 72, 673-685 (1964).

10. "Aluminum Alloy Castings, High Strength" - U. S. Military Specification MIL-A-21180B, issued 4 August 1960.

11. "Magnesium Alloy Castings, High Strength" - U. S. Military Specification MIL-M-46062 (MR), issued 25 June 1963.

12. K. E. Nelson - "New Specification for High-Strength Magnesium Castings" - Foundry 91(12), 58-61 (1963).

13. K. E. Mann - "High-Strength Magnesium Casting Alloys Containing Aluminum and Zinc" - Metall 18, 212-219 (1964).

14. "Recommended Practices for Sand Casting Aluminum and Magnesium Alloys" - 2nd edition, publ. Am. Foundrymen's Society (1965).

15. M. C. Flemings, P. J. Norton and H. F. Taylor - "Rigging Design of a Typical High-Strength, High-Ductility Aluminum Casting" - Trans. AFS 65, 550-555 (1957).

16. W. A. Bailey - "Comparative Strength of 354-T6 Al-Si-Cu-Mg Casting Alloy" - Trans. AFS 72, 790-797 (1964).

17. T. H. Owen and L. E. Marsh - "Mechanical Properties of C355 Aluminum Casting Alloy" - Metal Progress 72(2), 78-83 (1957).

18. J. W. Meier and A. Couture - "Effect of Casting Temperature on Aluminum Alloy Test Bar Properties" - Trans. AFS 68, 636-647 (1960).

19. W. A. Pollard - "Effect of Magnesium Content on Properties of Binary Al-Mg Alloys" - Trans. AFS 72, 587-590 (1964).

20. H. C. Rutemiller - "New Al-Mg-Zn Casting Alloy" - Trans. AFS 66, 222-224 (1958).

21. W. A. Bailey and E. N. Bossing - "Effect of Quenching on a Magnesium Casting Alloy" - Foundry 90(6), 88-89 (1962).

22. H. F. Honsel and P. Zimmermann - "Technology of High-Strength Magnesium Alloys" - Giesserei 50, 765-781 (1963).

23. F. Sauerwald - "The Magnesium-Zirconium Constitution Diagram" - Z. anorg. Chemie 225, 212-220 (1947).
F. Sauerwald - "The Effect of Zirconium on the Solidification of Magnesium Alloys and Some Properties of Cast Magnesium Alloys Containing Zirconium" - Z. Metallkunde 40, 41-46 (1949).

24. E. F. Emley - "Recent Advances in Magnesium Casting Alloy Technology" - Proc. 25th Internat. Foundry Congress, Brussels, pp. 358-392 (1958).

25. J. W. Meier and M. W. Martinson - "Development of High-Strength Magnesium Casting Alloy ZK61" - Trans. AFS 58, 742-751 (1950).

26. J. W. Meier - "Characteristics of High-Strength Magnesium Casting Alloy ZK61" - Trans. AFS 61, 719-728 (1953).

27. B. Lagowski and J. W. Meier - "Development of High-Strength Magnesium Casting Alloys Containing Silver, Zinc and Zirconium" - Trans. AFS 72, 310-320 (1964).

28. B. Lagowski and J. W. Meier - "Further Development of Mg-Zn-Ag-Zr Casting Alloys" - Trans. AFS 73 (1965).

29. J. W. Meier and B. Lagowski - "Development of Premium-Quality Magnesium Alloy Mortar Base Castings" - Proc. Magnesium Assoc., New York, A1-A11 (1964).

30. R. J. M. Payne and N. Bailey - "Improvement of the Age-Hardening Properties of Magnesium-Rare Earths Alloys by Addition of Silver" - J. Inst. Metals 88, 417-427 (1959/60).

31. D. J. Whitehead - "Magnesium-Silver-Didymium-Zirconium Casting Alloy QE22A" - Trans. AFS 69, 442-456 (1961).

32. A. V. Carless - "Metallurgical Control of Quality in the Production of Aluminum Alloy Castings" - J. Inst. Metals 85, 227-235 (1956/57).

33. E. F. Emley and P. A. Fisher - "The Control of Quality of Magnesium-Base Alloy Castings" - J. Inst. Metals 85, 236-254 (1956/57).

34. R. W. Ruddle and A. Cibula - "The Metallurgical Principles of the Control of Quality of Non-Ferrous Castings" - J. Inst. Metals 85, 265-292 (1956/57).

35. F. H. Smith - "Inclusions in Aluminum Alloy Castings" - Light Metals 23, 208-212 (1960).

36. R. J. Kissling and J. F. Wallace - "Fluxing to Remove Oxide from Aluminum Alloys" - Foundry 91(3), 76-81 (1963).

37. K. J. Brondyke and P. D. Hess - "Filtering and Fluxing Processes for Aluminum Alloys" - Trans. AIME 230, 1553-1556 (1964).

38. A. Buckeley - "Filtering of Light Alloy Melts" - Giesserei 51, 655-659 (1964).

39. W. E. Sicha - "Aluminum Casting Research" - Trans. AFS 71, 319-324 (1963).

40. R. J. Kissling and J. F. Wallace - "Gas Porosity in Aluminum Castings" - Foundry 91(2), 70-75 (1963).

41. M. J. Diamond - "Some New Processing and Quality Control Developments in Foundry Technology" - General Motors Eng. J. 11(2), 22-27 (1964); Foundry 92(9), 92-95 (1964).

42. E. M. Passmore, M. C. Flemings and H. F. Taylor - "Fundamental Studies on Effects of Solution Treatment, Iron Content, and Chilling of Sand-Cast Aluminum-Copper Alloys" - Trans. AFS 66, 96-103 (1958).

43. R. J. Kissling and J. F. Wallace - "Grain Refinement of Aluminum Castings" - Foundry 91(6), 78-82, and (7), 45-49 (1963).

44. C. E. Nelson - "Grain Size Behaviour in Magnesium Casting Alloys" - Trans. AFS 56, 1-23 (1948).

45. G. W. Form, G. K. Turnbull, G. Gould, H. Merchant and J. F. Wallace - "Grain Refinement of Cast Metals" - Proc. 27th Internat. Foundry Congress, Zurich, 167-187 (1960).

46. "Symposium on Sand-Cast Aluminum Alloy Test Bars" - 29th Internat. Foundry Congress, Detroit (1962); publ. Am. Foundrymen's Society, 1963, 54 pp.

47. "Gating and Feeding for Light Metal Castings" - publ. Am. Foundrymen's Society, 1962, 14 pp.

48. R. W. Ruddle - "The Running and Gating of Sand Castings" - publ. Inst. Metals, London, Monograph No. 19 (1956), 183 pp.

49. Series of articles on Gating and Risering (by various authors) - Foundry 87(10, 11); 88(4, 5); 89(2, 3, 8, 9), (1959-61).

50. R. F. Polich, A. Saunders and M. C. Flemings - "Gating Premium Quality Castings" - Trans. AFS 71, 418-426 (1963).

51. W. A. Pollard - "Metal Flow in Aluminum Test Bar Moulds by Fluorescent Screen Radiography" - Trans. AFS 71, 296-304 (1963).

52. M. C. Flemings - "Fluidity of Metals - Techniques for Producing Ultra-Thin Section Castings" - Proc. 30th Internat. Foundry Congress, Prague, pp. 61-81 (1963).

53. R. W. Ruddle - "The Solidification of Castings" - 2nd edition, publ. Inst. Metals, London, Monograph No. 7 (1957), 116 pp.

54. Series of articles on Solidification and Heat Treatment (by various authors) - Foundry 87(9), 84-101 (1959).

55. Symposium on Solidification (by various authors) - Trans. AFS 68, 145-156, 670-684, 691-695 (1960).

56. R. E. Spear and G. R. Gardner - "Solidification of Aluminum Casting Alloys" - Trans. AFS 68, 36-44 (1960).

57. W. C. Winegard - "An Introduction to the Solidification of Metals" - publ. Inst. Metals, London, Monograph No. 29 (1964), 98 pp.

58. B. Chamberlain and J. Sulzer - "Gas Content and Solidification Rate Effect on Tensile Properties and Soundness of Aluminum Casting Alloys" - Trans. AFS 72, 600-607 (1964).

59. R. A. Dodd, W. A. Pollard and J. W. Meier - "Hot Tearing of Magnesium Casting Alloys" - Trans. AFS 65, 100-117 (1957).

60. E. J. Gamber - "Hot Cracking Test for Light Metal Casting Alloys" - Trans. AFS 67, 237-241 (1959).

61. H. M. Skelly and D. C. Sunnucks - "Segregation in Magnesium-Rare Earths-Zinc-Zirconium Alloys" - Trans. AFS 62, 481-491 (1954).

62. M. C. Flemings - "Microsegregation in Castings and Ingots" - Trans. AFS 72, 353-362 (1964).

63. A. J. Iler - "Centrifugal Force Effect on Mechanical Properties of Aluminum Alloy 356 + Be Permanent Mould Casting" - Trans. AFS 69, 98-105 (1961).

64. W. C. Smith - "Centrifugal Casting of Thin-Walled Magnesium Parts" - Metal Progress 80(2), 101-102 (1961).

65. S. Z. Uram, M. C. Flemings and H. F. Taylor - "Effect of Pressure during Solidification on Microporosity in Aluminum Alloys" - Trans. AFS 66, 129-134 (1958).

66. J. L. Reiss and E. C. Kron - "Ultra-High Pressure Casting" - Trans. AFS 68, 89-96 (1960).

67. "Design Problems Involving Thin Sections" - Casting Design Handbook, publ. Am. Society for Metals, 1962, pp. 21-34.

68. J. B. Caine - "Care is Essential in Selecting Test Specimen" - Foundry 92(7), 40-43 (1964).

69. B. Lagowski and W. A. Pollard - "Inclusion Identification in Magnesium Alloy Castings" - Trans. AFS 68, 7-12, 828-830 (1960).

70. A. J. Iler - "Why Bother with Premium-Quality Castings" - Proc. Magnesium Association, 1962, 7 pp.; Foundry 91(5), 106-107 (1963).

71. J. Zotos - "Computers Open New Horizons in Casting Technology" - Proc. 31st Internat. Foundry Congress, Amsterdam (1964); Trans. AFS 72, 769-776 (1964).

72. J. Zotos - "Future Metallurgical Controls Utilizing the Computer" - Trans. AFS 92, 486-488 (1964).

73. B. H. Murphy - "Process Control by Computer" - Foundry 92(12), 54-57 (1964).

JWM:(PES):vb

TABLE 1

U. S. Production of Aluminum Alloy Castings
(According to U. S. Bureau of Mines)

Year	Total, 1000 t	Sand Castings		Permanent Mould Castings		Die Castings	
		1000 t	% of total	1000 t	% of total	1000 t	% of total
1945	186	98	52 ½	54	29	34	18½
1950	267	92	34 ½	91	34	84	31 ½
1953	327	107	33	100	30	120	37
1955	410	83	20	149	36½	178	43½
1960	387	65	16½	129	33½	193	50
1963	476	72	15	150	32	254	53

TABLE 2

U. S. Production of Magnesium Alloy Castings
(According to U. S. Bureau of Mines)

Year	Total, t	Sand Castings		Permanent Mould Castings		Die Castings	
		t	% of total	t	% of total	t	% of total
1945	25,526	21,236	83 ½	3,445	13 ½	845	3
1950	3,582	3,090	86	250	7	242	7
1953	17,813	14,306	80 ½	1,106	6	2,401	13½
1955	10,367	6,872	66	876	9	2,619	25
1960	4,834	2,561	53	745	15½	1,528	31½
1963	10,260	3,280	32	1,400	13 ½	5,580	54 ½

TABLE 3

Properties of Designated Areas of Premium Quality Castings (Aluminum Alloys)
(According to U. S. Military Specification MIL-A-21180B, dated 4 August 1960)

Alloy Designation	Class No.	0.2% YS kpsi (a)	0.2% YS kg/mm^2 (a)	UTS kpsi (a)	UTS kg/mm^2 (a)	El.,% in 4D (a)
A356	1	28	19.7	38	26.7	5.0
	2 (b)	30	21.1	40	28.1	3.0
	3 (b)	34	23.9	45	31.6	3.0
C355	1	31	21.8	41	28.8	3.0
	2 (b)	33	23.2	44	31.0	3.0
	3 (b)	40	28.1	50	35.2	5.0

NOTES: (a) Minimum properties of specimens cut out from designated areas of casting, produced by any casting process; special moulds, permanent moulds or sand moulds with chills may be used. Properties in other areas will vary with mould process and foundry techniques used.

(b) Classes 2 and 3 are obtainable in favourable casting configurations and must be negotiated with the foundry for the particular configuration desired.

TABLE 4

Mechanical Properties in Designated Areas of High-Quality Magnesium Alloy Castings
(According to U. S. Military Specification MIL-M-46062 (MR), dated 25 June 1963)

Alloy Designation	Designated Area Class	Minimum Properties in Designated Areas				
		UTS		0.2% YS		El.,%
		kpsi	kg/mm^2	kpsi	kg/mm^2	in 4D
AZ92A-T6	1	40	28.1	25	17.6	3
	2	34	23.9	20	14.0	1
	3	30	21.1	18	12.7	0.75
	X*	17	12.0	13.5	9.5	0.25
QE22A-T6	1	40	28.1	28	19.7	4
	2	37	26.0	26	18.3	2
	3	33	23.2	23	16.2	2
	X	28	19.7	20	14.0	2
ZK61A-T6	1	42	29.5	29	20.4	6
	2	37	26.0	26	18.3	4
	3	34	23.9	23	16.2	2
	X	30	21.1	21	14.8	1.25

* X - unspecified areas of casting.

TABLE 5

Tensile Properties of Some High-Strength Aluminum Sand-Casting Alloys

Alloy Designation	Nominal Composition, %	0.2% YS		UTS		El.,% in 4D	
		kpsi	kg/mm^2	kpsi	kg/mm^2		
a) Commercial Alloys							
SG70A-T6	7 Si-0.3 Mg	24	16.9	33	23.2	3.5	Typical, test bars(14)
A356	7 Si-0.3 Mg (HP)*	30	21.1	45	31.6	10	Test bars(3)
A356-T6	7 Si-0.3 Mg (HP)	26	18.3	31	21.8	1.5	Unchilled castings(15)
A356-T6	7 Si-0.3 Mg (HP)	33	23.2	42	29.5	6	Chilled castings(15)
var.356-T6	7 Si-0.6 Mg-0.15 Be (HP)	50	35.2	56	39.4	8	Chilled castings(16)
354-T6	9 Si-1.8 Cu-0.5 Mg (HP)	51	35.9	63	44.3	3	Chilled castings(16)
SC51A-T6	5 Si-1.3 Cu-0.5 Mg	25	17.6	35	24.6	3	Typical, test bars(14)
SC51A-T6	5 Si-1.3 Cu-0.5 Mg	30	21.1	39	27.4	4	Chilled castings(17)
C355-T62	5 Si-1.3 Cu-0.5 Mg (HP)	38	26.7	48	33.8	4	Chilled castings(17)
C4A-T6	4.5 Cu	24	16.9	36	25.3	5	Typical, test bars(14)
C4-T6	4.5 Cu (HP)	32	22.5	48	33.8	7	Test bars(18)
C4-T6	4.5 Cu (HP)	30	21.1	57	40.1	18	Chilled plates(2, 3)
G10A-T4	10 Mg	25	17.6	46	32.4	14	Typical, test bars(14)
G10-T4	10 Mg (HP)	27	19.0	55	38.7	30	Test bars(18)
G10-T4	10 Mg (HP)	28	19.7	57	40.1	35	Chilled plates(19)
b) Experimental Alloys							
-	Various	50-60	35-42	60-68	42-48	5-10	Unpublished work

* HP = high-purity alloy.

TABLE 6

Typical Tensile Properties of Magnesium Sand-Casting Alloys*
(Obtained on separately-cast test bars)

Alloy Designation	Nominal Composition, %	0.2% YS		UTS		El.%
		kpsi	kg/mm^2	kpsi	kg/mm^2	in 2 in.
a) Commercial Alloys(14)						
AZ91-T6	8.7 Al-0.7 Zn-0.3 Mn	19	13.4	40	28.1	5
AZ92-T6	9 Al-2 Zn-0.3 Mn	21	14.8	40	28.1	2
ZE41-T5	4 Zn-1.2 RE-0.7 Zr	20	14.1	30	21.1	4
ZH62-T5	5.5 Zn-1.8 Th-0.7 Zr	25	17.6	40	28.1	6
ZK51-T5	4.5 Zn-0.7 Zr	24	16.9	40	28.1	8
ZK61-T6	6 Zn-0.8 Zr	32	22.5	46	32.3	10
EZ33-T5	3.2 RE-2.6 Zn-0.7 Zr	15	10.5	23	16.2	3
HK31-T6	3.2 Th-0.7 Zr	15	10.5	32	22.5	8
HZ32-T5	3.2 Th-2.2 Zn-0.7 Zr	14	9.8	30	21.1	7
QE22-T6	2.5 Ag-2.2 RE-0.7 Zr	30	21.1	40	28.1	4
b) Experimental Alloys(27,28)						
ZQ32-T6	3 Zn-2 Ag-0.7 Zr	19	13.4	39	27.4	20
ZQ42-T6	4 Zn-2 Ag-0.7 Zr	26	18.3	44	31.0	17
ZQ52-T6	5 Zn-2 Ag-0.7 Zr	30	21.1	46	32.3	16
ZQ64-T6	6 Zn-4 Ag-0.7 Zr	35	23.2	50	35.2	8
ZQ71-T6	7 Zn-1 Ag-0.7 Zr	35	23.2	50	35.2	8
ZQ91-T6	9 Zn-1 Ag-0.7 Zr	34	23.9	49	34.4	7

* Alloy and temper designations according to Canadian designation codes CSA.H.1-1958.

TABLE 7

Properties of Premium-Quality Magnesium Alloy Castings(28)

Alloy Designation	Test Casting(a)	0.2% YS kpsi	0.2% YS kg/mm^2	UTS kpsi	UTS kg/mm^2	El.,% in 4D
AZ91-T6	A	21.2	14.9	42.2	29.7	4.5
	B	23.8	16.7	41.2	29.0	6.5
	C	22.4	15.8	41.4	29.1	5.0
	D	21.0	14.8	41.3	29.0	5.5
	E	21.1	14.8	44.9	31.6	6.5
AZ92-T6	A	24.8	17.4	43.7	30.7	2.5
	B	27.5	19.3	45.1	31.7	4.0
	C	26.8	18.8	42.9	30.2	3.5
	D	25.7	18.1	45.1	31.7	3.0
	E	29.1	18.5	46.3	32.6	3.0
QE22-T6	A	31.3	22.0	40.7	28.6	3.5
	B	31.0	21.8	38.8	27.3	2.0
	C	31.1	21.8	38.8	27.3	2.0
	D	29.9	21.0	40.3	28.3	4.5
	E	30.8	21.7	42.3	29.7	4.5
ZK61-T6	A	32.8	23.1	46.8	32.9	11.0
	B	33.6	23.6	46.6	32.8	8.0
	C	31.4	22.1	47.4	33.3	7.5
	D	31.3	22.0	46.4	32.6	15.0
	E	31.3	22.0	46.5	32.7	18.0
ZQ64-T6	A	34.3	24.1	48.9	34.4	10.5
	B	35.6	25.0	49.9	35.1	12.5
	C	34.5	24.2	47.8	33.6	7.5
	D	33.7	23.7	50.7	35.7	9.5
	E	35.4	24.8	50.8	35.8	10.0
ZQ71-T6	A	36.9	26.0	49.2	34.6	7.5
	B	36.7	25.8	47.8	33.6	7.0
	C	35.0	24.6	48.9	34.4	8.0
	D	34.4	24.2	49.3	34.7	10.0
	E	36.0	25.7	50.0	35.2	13.5
ZQ91-T6	A	36.7	25.8	49.8	35.0	9.0
	B	34.8	24.5	49.9	35.1	8.5
	C	33.9	23.8	48.2	33.9	5.5
	D	33.8	23.8	48.4	34.0	7.5
	E	34.9	24.5	50.9	35.8	13.5

(a) A - separately-cast test bar, 1/2-inch (12.7 mm) diameter.
B - 1/8-inch (3.2 mm)-thick unchilled plate.
C - 1/4-inch (6.4 mm)-thick unchilled plate.
D - 1/2-inch (12.7 mm)-thick unchilled plate.
E - 2-inch (50.8 mm)-thick,end-chilled plate (adjacent to chill).

TABLE 8

Tensile Properties of Test Bars Cut Out of Prototype Castings(29)

Alloy Designation			Designated Areas, Class 1						Unspecified Areas					Simulated Service Tests Breaking Load	
			UTS		0.2% YS		El.%		UTS		0.2% YS		El.%		
			kpsi	kg/mm²	kpsi	kg/mm²	in 4D		kpsi	kg/mm²	kpsi	kg/mm²	in 4D	1000 lb	1000 kg
AZ92-T6	max		46.2	32.5	25.6	18.0	4.5		38.9	27.4	25.2	17.7	2.0		
	min		41.7	29.3	20.2	14.2	3.5		35.1	24.7	20.5	14.4	1.0		
	ave	(6)	43.9	30.8	22.8	16.0	4.5	(6)	36.6	25.7	23.2	16.3	1.4	178	81
	MIL*		40	28.1	25	17.6	3		17	12.0	13.5	9.5	0.25		
QE22-T6	max		42.2	29.7	35.0	24.6	5.5		40.1	28.2	30.2	21.2	3.5		
	min		39.7	27.9	30.1	21.2	3.5		38.4	27.0	25.8	18.1	2.5		
	ave	(7)	40.7	28.6	33.4	23.5	4.3	(8)	39.3	27.6	28.3	19.9	2.7	217	98
	Mil*		40	28.1	28	14.0	4		28	19.7	20	14.0	2		
ZK61-T6	max		46.4	32.6	33.2	23.3	14.0		41.5	29.2	29.5	20.8	6.5		
	min		44.4	31.3	28.3	19.9	8.0		38.2	26.9	20.0	14.0	2.5		
	ave	(10)	45.5	32.0	31.8	22.4	10.0	(12)	39.4	27.7	25.9	18.2	4.1	236	107
	Mil*		42	29.5	29	20.4	6		30	21.1	21	14.8	1.25		
ZQ64-T6	max		49.2	34.6	40.1	28.2	9.5		45.9	32.3	30.1	21.2	7.0		
	min		48.7	34.2	32.8	23.0	8.0		39.2	27.6	19.1	13.5	4.5	254	120
	ave	(3)	49.0	34.5	36.0	25.3	8.5	(4)	42.9	30.2	26.0	18.3	6.0		

* Mil - minimum in Military Specification MIL-M-46062 (MR) dated 25 June, 1963.

NOTE: Numbers in brackets give number of specimens tested.
Test bars for Class 1 areas were cut out from 1-1/4-inch-thick sections.

TABLE 9

Comparison of Strength-to-Weight Ratios of Casting Materials

Casting Material	UTS		0.2% YS		El,% in 4D	Strength-to-Weight Ratio* ($kg/mm^2 : g/cm^3$)	
	kpsi	kg/mm^2	kpsi	kg/mm^2		UTS	0.2% YS
Aluminum Alloys							
Commercial	60	42.2	50	35.2	10	15.6	13.0
Experimental	65	45.7	55	38.7	10	16.9	14.3
Future	70	49.2	60	42.2	10	18.3	15.6
Magnesium Alloys							
Commercial	46	32.4	32	22.5	10	17.5	12.2
Experimental	52	36.6	40	28.2	10	19.8	15.2
Future	60	42.2	50	35.2	10	22.8	19.0
Steel Castings							
MIL-S-46052 (MR)	180	126.5	160	112.5	8	16.2	14.3
"	225	158.2	175	123.0	5	22.0	15.7
"	260	183.0	210	147.7	3	23.3	18.0

* Densities: 2.70 for aluminum, 1.85 for magnesium, and 7.85 for steel.

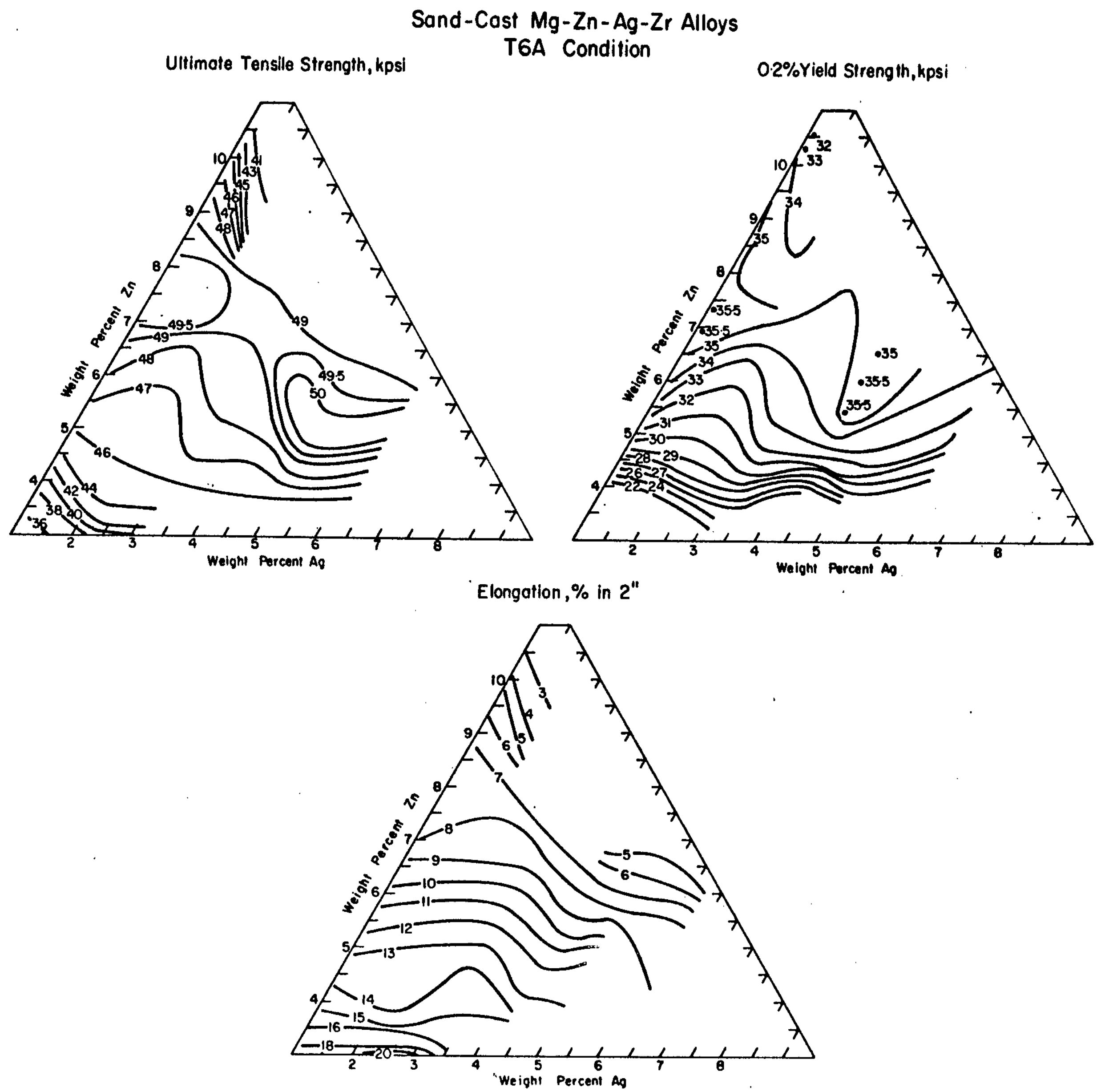

Figure 1. Average tensile property values for fully heat treated ZQ-type alloys, obtained on separately-cast test bars(28). (Values for ultimate tensile strength and 0.2% yield strength are given in 1000 psi. To convert to kg/mm^2, multiply by 0.7.)

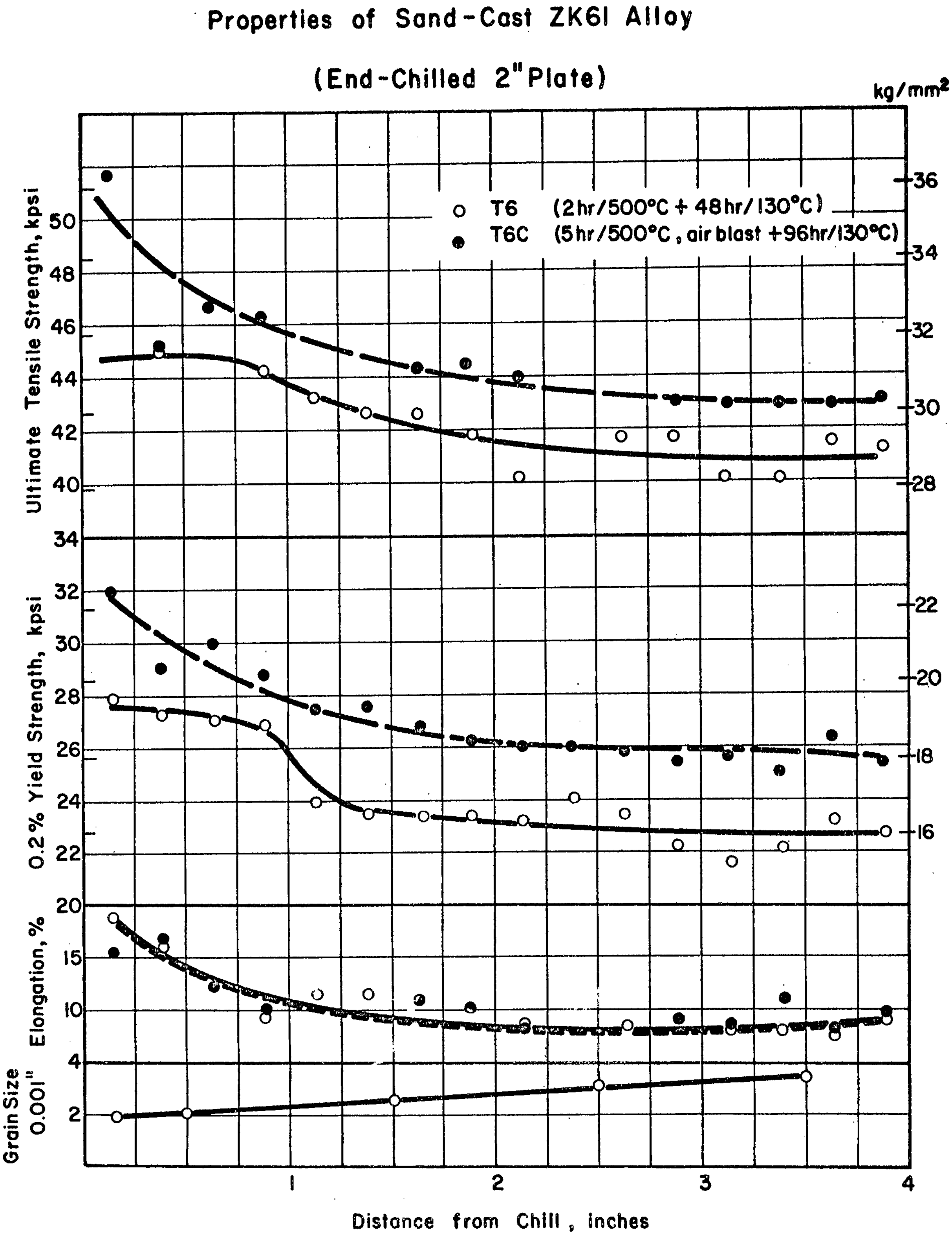

Figure 2. Effect of chilling on properties of sand-cast magnesium alloy ZK61-T6 (end-chilled 2-inch plate)[9].

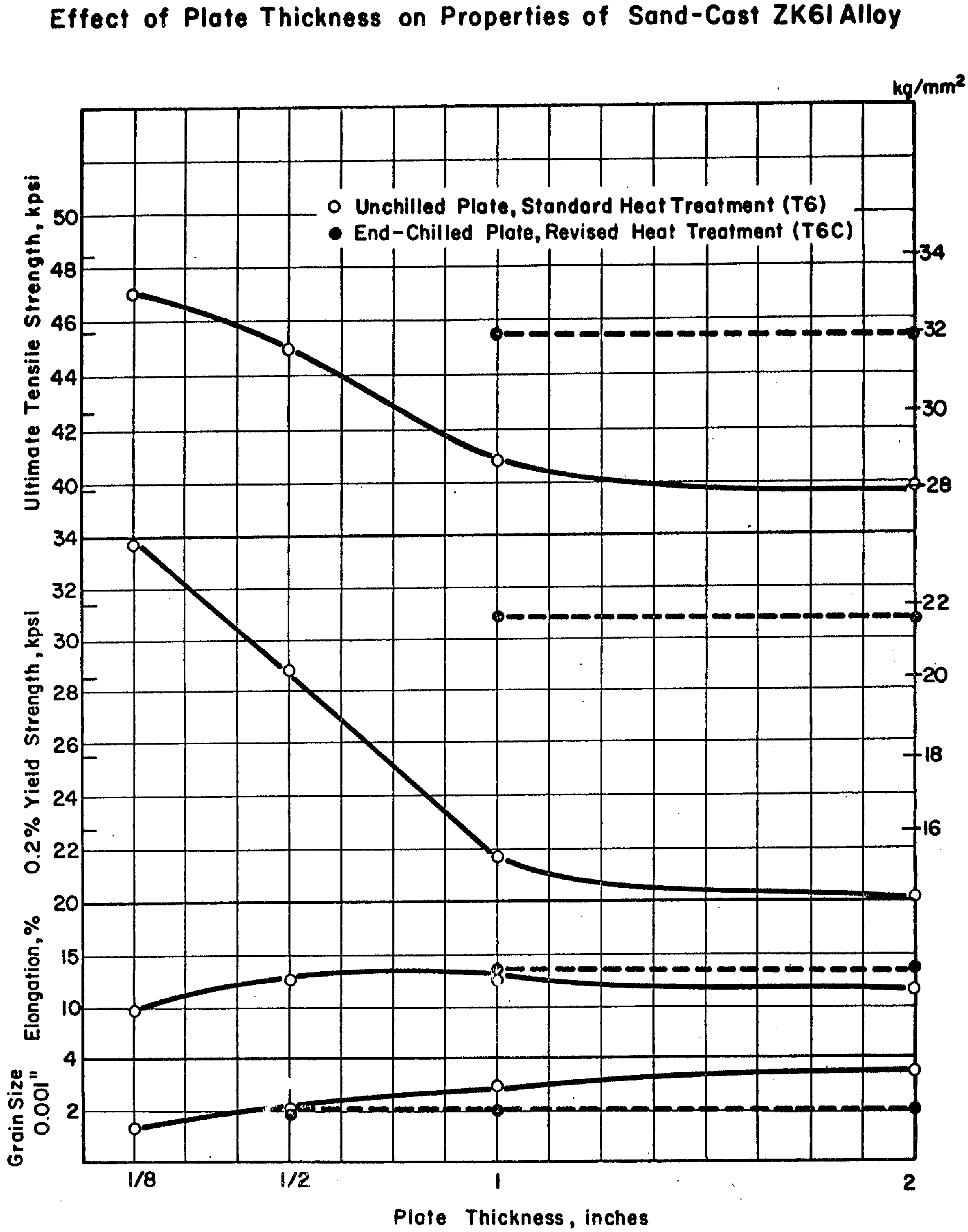

Figure 3. Effect of plate thickness on properties of sand-cast magnesium alloy ZK61-T6 (9).

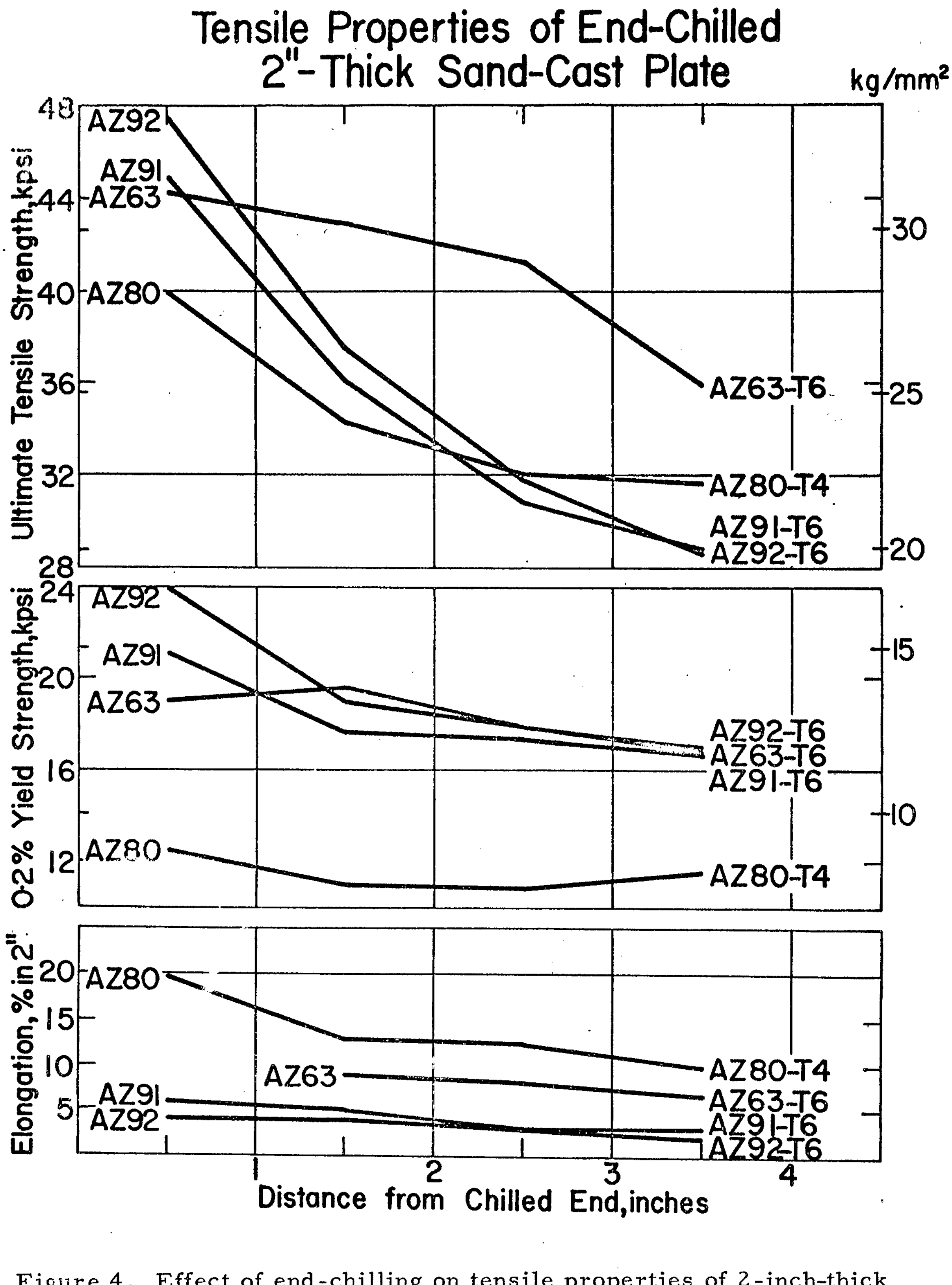

Figure 4. Effect of end-chilling on tensile properties of 2-inch-thick Mg-Al-Zn alloy plates (9).

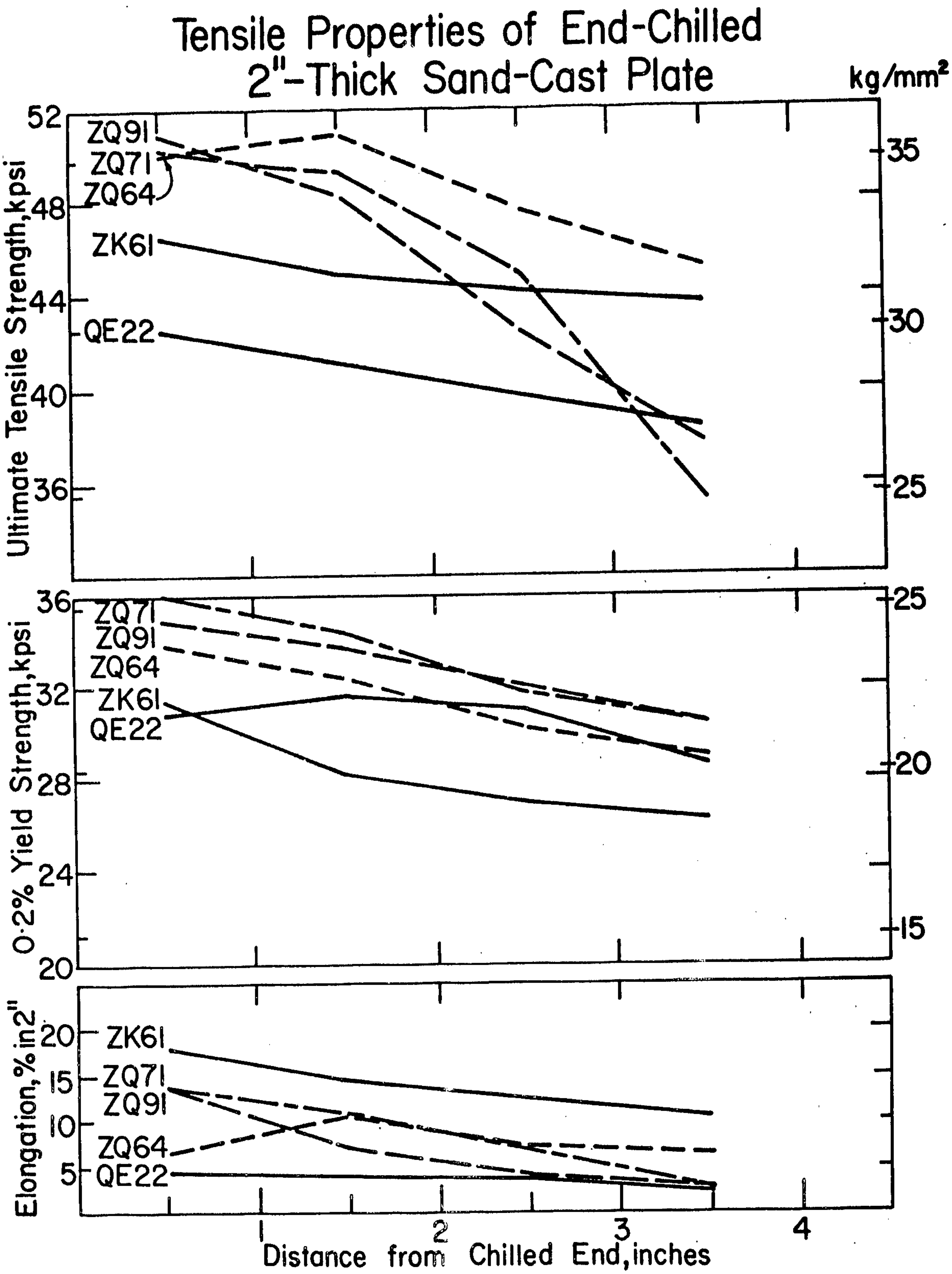

Figure 5. Effect of end-chilling on tensile properties of 2-inch-thick plates of high-strength magnesium alloys[9]. (All alloys heat treated to T6 temper).

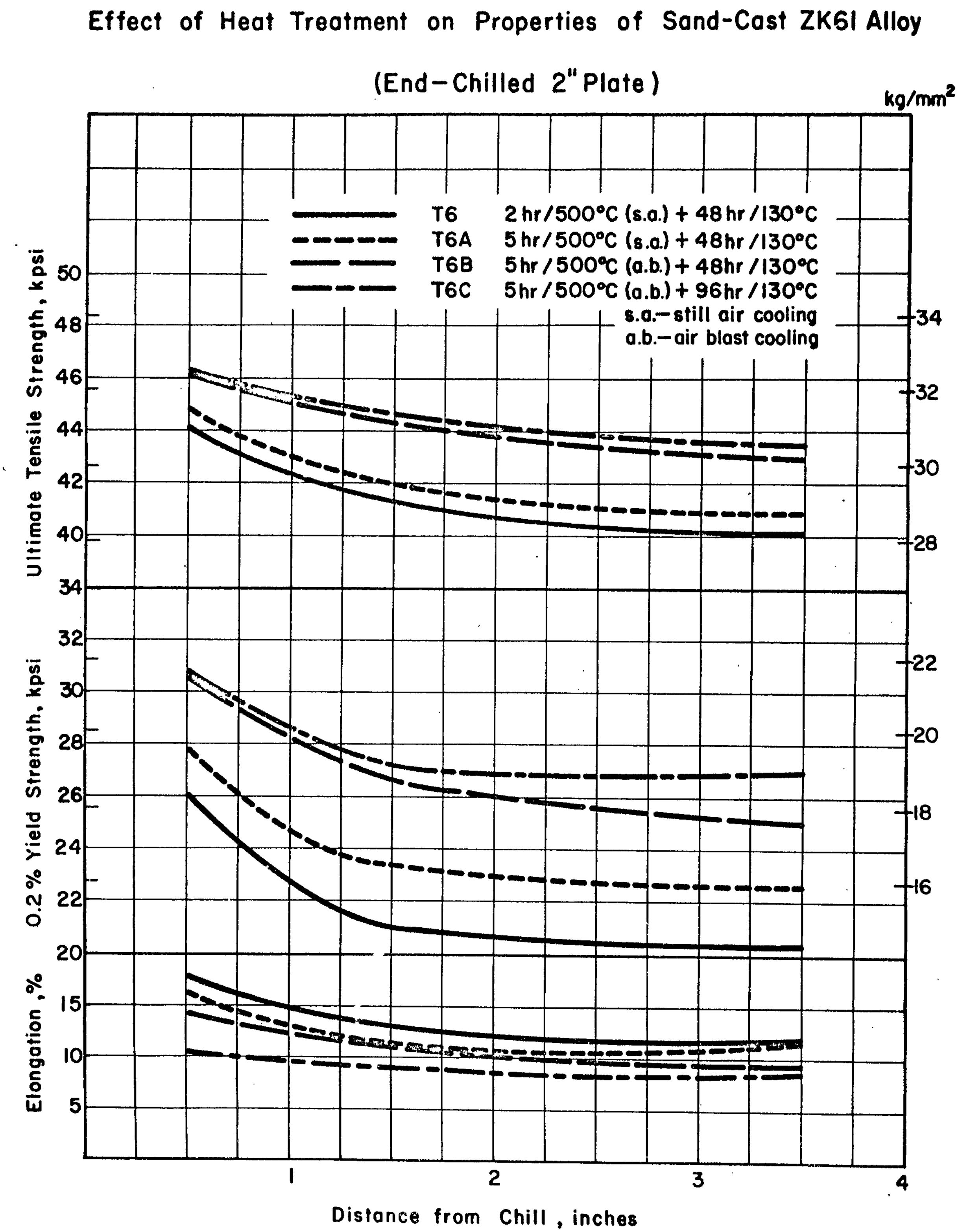

Figure 6. Effect of heat treatment on properties of sand-cast magnesium alloy ZK61-T6 (end-chilled 2-inch plate)[9].